

**UNITED STATES PATENT APPLICATION**

of

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for

**INTEGRATION OF A GAIN EQUALIZATION FILTER IN A GAIN MEDIUM**

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# INTEGRATION OF A GAIN EQUALIZATION FILTER IN A GAIN MEDIUM

## CROSS-REFERENCE TO RELATED APPLICATIONS

[001] This application claims priority to and the benefit of U.S. Provisional Patent Application No. 60/422,679, filed October 30, 2002, entitled Integration of Gain Equalization Filter in a Gain Medium; which is hereby incorporated by reference in its entirety.

## BACKGROUND OF THE INVENTION

### The Field of the Invention

[002] The present invention relates generally to optical amplifiers for amplifying a plurality of optical wavelength channels. More specifically, the invention relates to equalizing gain in an optical amplifier for a plurality of optical wavelength channels.

### The Relevant Technology

[003] In the field of data transmission, one method of efficiently transporting data is through the use of fiber-optics. Digital data is propagated through a fiber-optic cable using light emitting diodes or lasers. Light signals allow for high transmission rates and high bandwidth capabilities. Also, light signals are resistant to electro-magnetic interferences that would otherwise interfere with electrical signals. Light signals are more secure because they do not allow portions of the signal to escape from the fiber-optic cable as can occur with electronic signals in wire-based systems. Light signals also can be conducted over greater distances without the signal loss typically associated with electronic signals on wire-based systems.

[004] While signal loss in a fiber-optic cable is less than that in wire-based systems, there is nonetheless some signal loss over the distances that light signals may be transmitted. To compensate for the signal loss, optical amplifiers are used. Two common optical amplifiers are Raman amplifiers and Erbium Doped Fiber Amplifiers (EDFAs). Both of these amplifiers use characteristics of doped fiber-optic cables to amplify light signals.

[005] The amplifier pumps light onto the fiber-optic cable where the light is at a different frequency than the light signal that is to be amplified. As the light signal and pumped light travel along the fiber-optic cable, energy from the light that is pumped onto the fiber-optic cable is transferred to the light signal. Optical amplifiers use optical pumps, i.e. laser sources, to generate the light that is pumped into the fiber-optic cable.

[006] In some fiber-optic applications, multiple signals may be sent simultaneously by using different wavelengths of light. Each wavelength may be referred to as a channel. For example, the C-band might be used to transmit 40 different channels or wavelengths along the 1530 to 1562 nm bandwidth. In a variety of optical applications it is desirable to amplify each channel with about the same optical gain. However, the optical gain of an optical gain medium, such as the doped fiber-optic cables, depends upon wavelength. Some wavelength channels will experience greater amplification than others. Consequently, a single gain medium does not usually function as a high gain medium having substantially uniform optical gain over an extended wavelength range.

[007] Conventional approaches to providing uniform optical gain over an extended wavelength range typically have more components than desired, require significant numbers of optical interconnects resulting in insertion losses, and typically cost more

than desired. Illustratively, EDFAs are widely used to amplify optical signals to compensate for transmission losses and insertion losses caused by interconnection of components and the gain characteristics of EDFAs are a strong function of optical wavelength. Therefore, to achieve substantially uniform optical gain over an extended wavelength for an EDFA requires an additional gain equalization filter (GEF). In a single stage amplifier, GEFs are commonly placed after the final stage of the amplifier. For multi-stage amplifiers, GEFs are sometimes placed between amplifier stages. Each GEF introduces an additional component cost, component size, and requires appropriate packaging to permit it to be optically coupled to other components. Further, physically coupling components together results in some degree of insertion loss for each physical connection.

## BRIEF SUMMARY OF THE INVENTION

[008] These and other limitations are overcome by the present invention which relates to systems and methods for equalizing optical gain across multiple wavelengths. In one embodiment of the invention, an optical waveguide is used to both amplify a light signal and equalize the optical gain of the various channels in the light signal. The optical waveguide includes at least one gain section to facilitate optical gain of the light signal. The optical waveguide further includes a gain equalization filter to substantially equalize the optical gain over a bandwidth range for which the gain section exhibits non-uniform optical gain.

[009] Another embodiment of the invention includes an optical amplifier. The optical amplifier includes an optical waveguide where the optical waveguide has at least one gain section and a gain equalization filter. A pump laser is coupled to the optical waveguide. The pump laser is configured to pump light onto the optical waveguide for amplifying a signal input into the optical waveguide.

[010] Embodiments of the invention reduce insertion losses in optical amplifiers by including a gain equalization filter in the optical waveguide that has been configured to provide gain to a light signal. Embodiments of the invention further reduce the number of components and interconnections in optical amplifiers by integrating a gain equalization filter into a gain medium.

[011] These and other advantages and features of the present invention will become more fully apparent from the following description and appended claims, or may be learned by the practice of the invention as set forth hereinafter.

## BRIEF DESCRIPTION OF THE DRAWINGS

[012] In order that the manner in which the above-recited and other advantages and features of the invention are obtained, a more particular description of the invention briefly described above will be rendered by reference to specific embodiments thereof which are illustrated in the appended drawings. Understanding that these drawings depict only typical embodiments of the invention and are not therefore to be considered limiting of its scope, the invention will be described and explained with additional specificity and detail through the use of the accompanying drawings in which:

[013] Figure 1 illustrates one embodiment of a gain equalization filter integrated in the gain medium;

[014] Figure 2 illustrates an exemplary erbium doped amplifier that implements a gain equalization filter;

[015] Figure 3 illustrates an exemplary erbium doped fiber configuration that includes an equalization filter;

[016] Figure 4 illustrates a simulated filter response of a gain equalization filter;

[017] Figures 5A-5D illustrate simulations of power spectra at different locations of an erbium doped fiber that includes a gain equalization filter; and

[018] Figure 6 compares a simulation of the erbium doped fiber amplifier performance with and without an integrated gain equalization filter.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[019] Amplifiers provide gain to optical signals. As previously stated, however, optical signals often have multiple wavelengths or channels and the gain of each wavelength in optical amplifiers is often related to the wavelength of the optical signals. This results in an undesirable situation where different wavelengths or channels have different gain. The present invention relates to systems and methods for equalizing the gain of wavelengths or channels in an optical signal. In one embodiment of the present invention, at least one gain equalization filter (GEF) is integrated into an optical waveguide structure that includes one or more gain sections. By integrating the GEF with the gain sections in an optical waveguide, insertion loss and component cost are reduced when compared to an assembly of discrete components. Optical signals entering the waveguide experience amplification in gain sections of the waveguide and wavelength selective attenuation in the GEF section(s) of the waveguide, thereby equalizing the gain of the optical amplifier across multiple wavelengths or channels.

[020] The optical waveguide 100 in Figure 1 is an example of a waveguide that includes a GEF section 102 disposed between a first gain section 104 having a first length and a second gain section 106 having a second length. More generally, however, it is understood that the present invention may be expanded to include other configurations, such as a GEF integrated with a single gain section, multiple GEF sections, such as additional GEF sections disposed proximate one or more ends of the gain sections, or amplifiers having three or more gain sections coupled by two or more GEF sections.

[021] In the embodiment illustrated in Figure 1, light input to the first end 108 of the waveguide 100 is amplified in the first gain section 104, which may for example, be

designed to function as a high gain, low noise gain section. The optical gain in the first gain section 104 depends upon wavelength. Consequently, after traveling through the length of the first gain section 104, some wavelengths or channels are amplified more than other wavelengths. The GEF section 102 has loss characteristics selected to reduce the non-uniformity in gain associated with the first gain section 104. Additionally, the GEF section 102 may be designed to pre-compensate for gain non-uniformities in subsequent gain sections. Any number of GEFs can be integrated with any number of gain sections in any order.

[022] The waveguide 100 may be an optical fiber, such as a single mode fiber, a multimode fiber, or a double clad fiber, although it is understood that other types of waveguides may also be used. Examples of gain medium for optical fibers include but are not limited to, fibers doped with Erbium, Yb, Sm, Tm or any combination thereof, because these materials may be optically pumped to provide gain at common optical network wavelengths.

[023] A variety of techniques may be used to form a GEF in a waveguide. For example, the GEF can be a UV written Bragg grating in the gain medium, a mechanical perturbation, electrically induced grating or an etched grating. The shape of the optical loss characteristics of the GEF may be selected using a variety of techniques. For example, if the GEF is formed from Bragg gratings, a series of Bragg gratings at different Bragg wavelengths may be formed to create a composite loss characteristic to flatten the optical gain. A GEF may be formed inside the core of the waveguide, in the cladding, or in both. A GEF formed from one or more gratings may use a variety of grating designs, such as slanted or unslanted gratings, Bragg gratings or long period gratings.



[024] One embodiment of the present invention is an erbium doped fiber amplifier (EDFA). Figure 2 shows an exemplary EDFA 200 including a segment of erbium doped fiber (EDF) 202 including an integrated GEF 204. Other components include a pump laser 206 for providing light at a pump wavelength, an input detector 208 for monitoring input power, an output detector 210 for monitoring output power, a controller 212 for selecting the pump power level, an input tap 214 for tapping off a portion of an input signal to the input detector 208, an output tap 222 for tapping off a portion of the amplified signal to the output detector 210, optical isolators 216 and 218 to reduce harmful back reflections, and a multiplexer 220 to couple input wavelength channels and pump laser 206 lighting to an input end of the EDF 202.

[025] Referring to Figure 2, amplifying a light or optical signal is demonstrated. A light signal is input into the input 224 of the EDFA 200. A portion of the light signal is tapped by the input tap 214. This portion of the light signal is detected by the detector 208, that may be a photo diode or other suitable photo detector that converts information about the light signal into a first electronic signal 209. The first electronic signal 209 is received by a controller 212 and is used in regulating the EDFA 200.

[026] The remainder of the light signal that was not tapped by the input tap 214 is passed through an optical isolator 216 that prevents back reflections. The light signal is then fed into a multiplexer 220. Meanwhile, the controller 212 controls a pump laser 206 that is also connected to the multiplexer 220 for pumping light into the multiplexer where the pumped light will be multiplexed with the light signal. The pump laser 206, in this example, is controlled by a signal input at an external control 228 and based on the value of the first electronic signal 209 from the detector 208. The external control 228 may provide the desired output power information for each channel. The external

control 228 may also specify the spectrum shape of output signals across all the channels over a whole wavelength band. Based on the value of the first electronic signal 209 from the detector 208, decisions can be made on how much pumping power is needed by the EDFA 200. The multiplexed light signal and pumped light is propagated onto the EDF 202 to create an amplified light signal. As previously mentioned, the EDF 202 includes a GEF 204 for equalizing the gain of the EDF 202 across a given bandwidth or range of wavelengths.

[027] One example of a broadband EDF is the Lucent GP-980 Erbium-Doped Fiber sold by OFS Specialty Photonics Division of Somerset, New Jersey. The EDF has a high erbium concentration while aluminum co-doping maintains good efficiency and spectral flatness over the C-Band (1530-1565 nanometers). EDFs such as the GP-980 may be purchased in pre-selected fiber lengths or in spools. In one embodiment, the EDF is a segment of GP-980 fiber approximately six meters in length having a GEF formed on a portion of the fiber.

[028] The amplified signal passes through the optical isolator 218 and to an output tap 222 where a portion of the amplified signal is fed into the output detector 210. The output detector 210 converts the portion of the amplified signal into a second electronic signal 211 containing information about the amplified signal. This second electronic signal 211 can be fed into the controller 212 where the information contained in the electronic signal can be used by the controller 212 in controlling the pump laser 206. The remaining portion of the amplified signal that is not tapped by the output tap 222 is transmitted to the output 226 of the EDFA 200 where it may be transmitted onto a fiber-optic network, or to some other fiber optic component.

[029] Figure 3 illustrates an exemplary EDF 300 having a length of 6 meters. A GEF section 302 is positioned 2 meters from the input end 308 of the EDF 300. Point A corresponds to an input end 308 of the EDF, the region between points A and B corresponds to a first gain section 304, the region between points B and C corresponds to the GEF section 302, and the region between points C and D corresponds to a second gain section 306 having an output at point D.

[030] The length of each gain section and the optical pump power level determine the required loss characteristics of the GEF. For a low noise, high gain amplifier, the first gain section 304 may, for example, be selected to be long enough to provide an initial desired minimum gain for all wavelength channels for the pump power level. The second gain section 306 may, for example, be designed to provide a higher-level of amplification than the first gain section 304 and consequently have a longer length.

[031] OFS also provides an Optical Amplifier Simulation System (OASiX), which models the performance of erbium-doped fiber in design simulations. In a simulation, two simple Gaussian shape filters were used to generate the GEF shape for the EDFA. The Gaussian filters may, for example, be formed from two Bragg gratings formed on a portion of the fiber. Figure 4 shows the frequency responses of a first Gaussian filter 402 and a second Gaussian filter 404 and their combined profile 406. Each Gaussian filter is formed as described above in a portion of the EDF. It will be understood, of course, that more complex filter designs may be used in addition to that shown in Figure 4.

[032] A computer simulation was performed assuming a pump power level input of 30 mW inside the EDF at a wavelength of 977 nm. The input signals have a total of

40 wavelengths in the C-band (1530-1562 nm) at a signal power of -40 dBm/channel. Figure 5A shows a simulation of the input power levels at point A (Figure 3) which are assumed to have equal input power levels. Figure 5B shows a simulation of the input power levels at point B (Figure 3). Because the gain of the EDF depends upon wavelength, the power level is non-uniform. Figure 5C shows the power level at point C (Figure 3) after passing through the GEF. The loss characteristics of the GEF may be selected to compensate for the non-uniform gain between points A and B and to also at least partially pre-compensate for non-uniform gain in the subsequent gain region 306 (Figure 3). Figure 5D shows the gain at the output of point D (Figure 3).

[033] Figure 6 shows a comparison of gain for an EDF with a GEF and also for an EDF without a GEF. Without the integrated GEF, over a 10 dB difference was noted across the channels as shown by the plot 602. By using the integrated GEF in the EDF, the gain flatness of the 40 channels can be easily controlled to within 2 dB as shown by the plot 604 which is enough for applications such as metro networking applications and the like. Furthermore, simulation also shows that the gain enhancement can be achieved in the long wavelength side of the 40 channels by using the integrated GEF.

[034] The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.